Driving Innovation in 6G Wireless Technologies: The OpenAirInterface Approach

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Abstract

The development of 6G wireless technologies is rapidly advancing, with the 3rd Generation Partnership Project (3GPP) entering the pre-standardization phase and aiming to deliver the first specifications by 2028. This paper explores the OpenAirInterface (OAI) project, an open-source initiative that plays a crucial role in the evolution of 5G and future 6G networks. OAI provides a comprehensive implementation of 3GPP and O-RAN compliant networks, including Radio Access Network (RAN), Core Network (CN), and software-defined User Equipment (UE) components. This paper details the history and evolution of OAI, its licensing model, and the various projects under its umbrella, such as RAN, the CN, and the Operations, Administration and Maintenance (OAM) projects. It also highlights the development methodology, Continuous Integration/Continuous Delivery (CI/CD) processes, and end-to-end systems powered by OAI. Furthermore, the paper discusses the potential of OAI for 6G research, focusing on spectrum, reflective intelligent surfaces, and Artificial Intelligence (AI)/Machine Learning (ML) integration. The open-source approach of OAI is emphasized as essential for tackling the challenges of 6G, fostering community collaboration, and driving innovation in next-generation wireless technologies.

Keywords:
OpenAirInterface, 6G Networks, Open RAN, Open-Source Software

1. Introduction

The year 2024 marks an important milestone in the development of 6th generation (6G) mobile communication systems as the 3rd Generation Partnership Project (3GPP), the institution that has standardized mobile communication systems since the 3rd generation, has entered the pre-standardization phase of

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6G. It has committed to deliver the first version of the specifications in Release 21, which is scheduled to be completed by the end of 2028 [1].

While the exact definition of 6G is still in flux, a high-level set of use cases and requirements has already been specified by the International Telecommunication Union (ITU) [2]. These include going beyond the IMT-2020 requirements, such as improved throughput, latency, reliability, spectral efficiency, to include Integrated Sensing and Communication (ISAC), Ubiquitous Connectivity, and Artificial Intelligence (AI). Moreover, four overarching aspects act as design principles commonly applicable to all usage scenarios: sustainability, connecting the unconnected, ubiquitous intelligence, security, and resilience [2].

From a technical perspective, the community has so far agreed on only a few high-level design principles. In particular, the 6G Radio Access Network (RAN) should be backwards compatible with 5G and able to connect to an evolution of the 5G Core Network (CN), 6G should support standalone operation only with spectrum sharing between 5G and 6G, and 6G should include open interfaces to foster a healthy ecosystem [1]. Moreover, 6G shall be able to leverage new spectrum opportunities, especially in the upper-mid band around $6-15$ GHz [3]. More elaborate studies about the use cases, architectures, and possible candidate technologies for 6G can be found in whitepapers from the O-RAN next generation research group [4] or the EU flagship project HEXA-X-II [5].

Another fact about 6G is that it will rely much more on open-source software than previous generations. 5G networks were the first to embrace virtualized deployments and open interfaces, thanks to the Service Based Architecture (SBA) of the 3GPP CN as well as the open RAN architecture specified by the O-RAN ALLIANCE [6]. Moreover, many of these virtualized network functions are readily available as open-source software [7, 8], bringing unprecedented flexibility to 5G systems, making them accessible to a much broader community of researchers and developers, and enabling rapid prototyping and experimentation. Open source will play an even more important role in the development of 6G, where it can serve as early implementations that inform and influence formal standardization processes, making it easier for the ecosystem to converge to practical and scalable solutions for future networks.

This paper presents OpenAirInterface (OAI), an open-source project that today allows users to easily deploy an end-to-end 3GPP and O-RAN-compatible 5th generation (5G) network based on Commercial Off-the-Shelf (COTS) hardware and interoperable with a wide range of User Equipments (UEs). In our previous work [9], we have shown how OAI has democratized 5G research through open-source access. In this work, we now present the latest advancements in OAI and our vision for evolving this platform toward 6G. We emphasize the importance of our open-source approach and highlight that the challenges of 6G can only be tackled by a community effort based on open-source components. We believe that this paper can serve as a reference for the wireless research and development community interested in deploying, extending, and experimenting with end-to-end mobile networks based on OAI.

This paper is structured as follows: in the remainder of this section, we give a historical overview of the evolution of the OAI project as well as the OAI public license. In Section 2, we present the current state-of-the-art and roadmaps of the different projects under the OAI Software Alliance (OSA) umbrella, i.e., RAN, CN, and Operations, Administration and Maintenance (OAM). In Section 3, we present the community-driven development methodology, the contribution process, as well as the Continuous Integration/Continuous Delivery (CI/CD) process. These processes make OAI stand out from other projects in the field. In Section 4, we give examples of end-to-end deployments of OAI that showcase the versatility of the software. In Section 5, we give our vision of 6G and show how OAI is already used today to showcase some of the features that might make it into 6G. Finally, we draw our conclusions in Section 6.

1.1. OpenAirInterface History and Evolution

The OAI project was founded in the early 2000s by EURECOM, a research center and graduate school in Sophia-Antipolis in the south of France. The goal of the project was to bridge the gap between industry and academia by giving researchers an open platform that was as close as possible to the real 3GPP cellular network. The platform was based on the Software-defined Radio (SDR) concept, where all the signal processing runs on a general-purpose processor, such as an Intel x86, with dedicated hardware only for analog blocks, such as up and down-conversion, as well as the Radio Frequency (RF) transmission and reception chains. Since at the time this technology was still in its infancy and no off-the-shelf devices were available, EURECOM researchers developed these radio cards themselves [10].

The first versions of OAI were only focused on the RAN and were not interoperable with any third-party core network or user equipment. OAI first gained widespread attention with the release of 4th generation (4G) Long Term Evolution (LTE) software around 2010 that made use of the widely available Universal Software Radio Peripheral (USRP) SDRs from Ettus Research [11] and that was interoperable with LTE smartphones as well as a third-party 4G Evolved Packet Core (EPC) [12].

This success story also sparked a lot of interest in both academia and industry, which led EURECOM to create the OSA in 2014 to support the growing developer and user community and streamline contributions to the code. OSA coordinates software contributions from its contributor community and ensures code quality through a well-established review process and a sophisticated CI/CD process based on a test and integration lab it maintains. This testing and integration leverages software simulators, third-party equipment, as well as an over-the-air indoor and outdoor testing environment.

OSA maintains a transparent software development process open to the entire OAI community and publishes a feature roadmap for each of its active projects. OSA is governed by its board of directors, which is composed of representatives of its founding member, EURECOM, and its strategic partners, which represent a diverse and balanced group of key equipment manufacturers, operators, silicon vendors, software distributors, and startups [13]. The strategic members and the OSA for-profit associate partners commit financial resources for OSA that allow the organization to maintain a core team of engineers managing code development, testing, and integration. Non-profit and academic institutions can become associate partners for free and nonetheless contribute to the development of the OAI software and use it for their research needs.

The OSA delivered the first version of a 5G RAN capable to support 5G Non Standalone (NSA) in 2020 and a 5G CN and 5G RAN capable to support 5G Standalone (SA) in 2021 [9]. Since then, OSA and several contributors from academia and industry have been evolving OAI constantly, integrating additional interfaces such as 3GPP F1 and E1 interfaces, the Small Cell Forum (SCF) Functional Application Platform Interface (FAPI) [14], and the O-RAN 7.2 fronthaul, E2, and O1 interfaces. Today, OAI can be deployed on a variety of platforms ranging from fully virtualized cloud platforms to bare metal. It is interoperable with a wide range of 3rd party hardware and software such as Radio Units (RUs) and SDRs, inline and look-aside hardware accelerators, O-RAN compatible RAN Intelligent Controllers (RICs) and Service Management and Orchestration (SMO) frameworks, as well as CNs. The OAI software assets also offer a standard-compliant test UE, an element of fundamental importance for 6G experimentation. We discuss the current capabilities of OAI in detail in Section 2.

The OSA also maintains a strong relationship to other organizations, such as the O-RAN ALLIANCE [15], the Linux Foundation [16], as well as the Small Cell Forum [17] to ensure the seamless integration of the OAI software into the broader 5G and 6G open-source ecosystem.

1.2. The OAI Public License

One of the major contributions of the OSA to the open-source community is the introduction of the OAI Public License. Cellular systems are collectively standardized by the industrial players in the 3GPP forum. Each player in this process of building consensus contributes technology components from its Intellectual Property Rights (IPR) portfolio. Once procedures are standardized, 3GPP acknowledges and recognizes the IPR contributions by different parties therein. To facilitate the adoption of the standardized technology, the organizations that own these patents collectively agree to make the IPR available to other parties through Fair, Reasonable, And Non-Discriminatory (FRAND) terms. The global adoption of 4G and 5G technologies is a remarkable evidence of the success of the above-mentioned process.

On the other hand, the Open Source Initiative (OSI) [18] that promotes licenses whose well-known examples include the Apache v2.0, MIT, and the GNU General Public License series, calls for free (meaning royalty-free, i.e., free from patents) redistribution of software.[1]

[1] The first versions of OAI were published under the GNU General Public License version 2 [19].

Cognizant of the divide in 3GPP standardization practices and limitations of the OSI approach producing open-source implementations for this industry, the OSA, in collaboration with its 3GPP-invested partners, drafted the OAI public license Version 1.1 in 2017 [20]. This license is a modified version of Apache v2.0 License, incorporating an additional clause that allows contributing parties to grant patent licenses to third parties. This clause brings clarity to the use of OAI software and aligns the software (re)-distribution policy to that of the 3GPP-standardized essential technology, which operates under FRAND terms for commercial usage.

The OAI Public License therefore enables the holders of 3GPP Standard Essential Patent (SEP) to contribute 3GPP procedures to the OAI source code in confidence under terms called out in the license and in alignment with the practices of this industry. These SEP can be found in the European Telecommunications Standards Institute (ETSI) intellectual property rights online database [21].

1.3. Related Work

In this subsection, we discuss other open-source projects that are in direct "competition" with OAI, i.e., that also implement different parts of 5G RAN or CN. For a comprehensive overview of other open-source projects related to building a fully virtualized and orchestrated 5G network, please refer to [8].

The srsRAN project [22] provides an open-source implementation of both Central Unit (CU) and Distributed Unit (DU), which is interoperable with SDRs like the USRPs, as well as with O-RAN RUs (O-RUs). For the latter, they provide their own fronthaul library and do not rely on the fronthaul library from the O-RAN Software Community (OSC) like OAI. The feature set of srsRAN CU and DU is comparable to that of OAI, except that they do not (yet) support CU control- and user-plane separation, Sounding Reference Signal (SRS), and Frequency Range 2 (FR-2). However, the main difference is their licensing model. They follow a dual licensing model where, on one hand, they provide all of their code under the GNU Affero General Public License v3.0 and, on the other hand, they offer a commercial license through their company, called Software Radio Systems. A more detailed comparison of OAI and srsRAN can be found in [23, 24].

On the side of the CN, there are two notable open-source projects: Free5GC is a Linux Foundation project published under Apache License 2.0 [25] and Open5GS is backed by NewPlane Inc. and published under the GNU Affero General Public License v3.0 as well as under a commercial license [26]. In general, OAI CN provides a similar set of features in comparison with these open-source projects, but since OAI CN is strongly used in research projects, it has some advanced features not present in the other projects. For example we i) provide a high-performance User Plane Function (UPF) (OAI can achieve nearly 100 gigabits per second throughput); ii) implement a cloud-native core with a collection of microservices following open, flexible and extensible principles; iii) support advanced features including Localization Management Function (LMF),

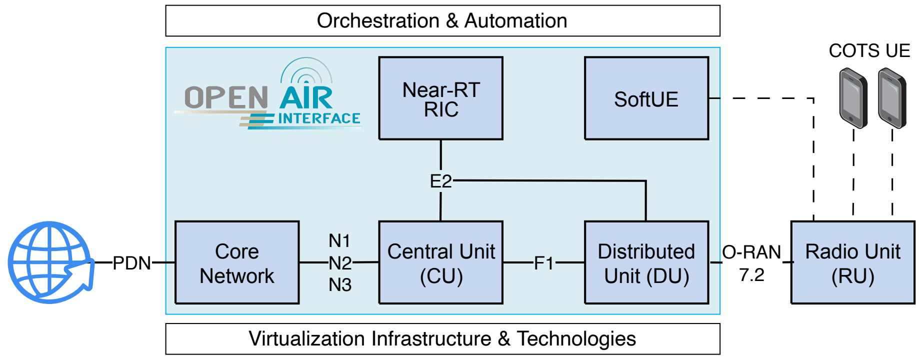

Figure 1: Simplified schematic of a 5G network showing which parts are covered by the OAI project. All parts of the OAI software can be run on fully virtualized hardware and can be managed by 3rd party orchestration and automation platforms.

Time Sensitive Networking (TSN), iv) providing support for AI/Machine Learning (ML)-based Services, enabling Network Automation for 5G, and providing exposure, and communication enhancements.

2. OpenAirInterface Projects

Figure 1 shows a simplified scheme of a 5G network showing the CN, the RAN consisting of CU, DU, and RU, the RIC, as well as the UE. The components enclosed in the light blue box are the ones covered by the OAI project, and that we are going to describe in more details in this section. All parts of the OAI software can be run on fully virtualized hardware and can be managed by 3rd party orchestration and automation platforms, which we will briefly describe at the end of this section.

The OSA maintains a roadmap for each of its projects on its webpage [27]. The roadmap is updated approximately every six months and reflects the plan of the development team at the OSA as well as commitments from the broader OAI community. The planning horizon is about one year, and the dates on the roadmap are the dates when we expect to merge the feature into the *develop* branch. Most of the features will already be available earlier through the feature branches.

Today, the software supports 4G, 5G NSA, as well as 5G SA architectures. In the following, however, we focus exclusively on the features of the 5G SA implementation.

2.1. Radio Access Network

Figure 2 shows the basic architecture of a 5G RAN including O-RAN interfaces. The OAI RAN project implements the CU and DU network functions together with all the necessary 3GPP and O-RAN interfaces. OAI also has an implementation of a RIC, which is described in detail in Section 2.2. The OAI

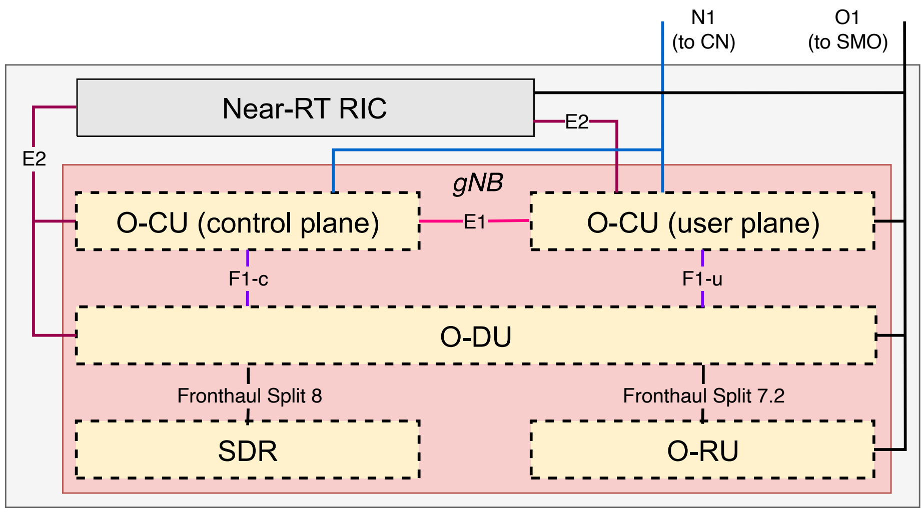

Figure 2: 5G RAN architecture including O-RAN interfaces

RAN can be deployed with the full F1 and E1 splits, i.e., with CU User Plane (CU-UP), CU Control Plane (CU-CP), and DU, or it can also be configured as a monolithic Next Generation Node B (gNB).

The OAI DU implements Radio Link Control (RLC), Medium Access Control (MAC), and the Physical (PHY) layers of the protocol stack. It can interface with SDRs like the USRP as well as commercial RUs, either using eCPRI split 8 or the O-RAN split 7.2 fronthaul interface, respectively. OAI has been tested successfully with O-RUs from VVDN, Benetel, LiteOn, and Foxconn [28].

The PHY supports static Time Division Duplexing (TDD) as well as Frequency Division Duplexing (FDD), subcarrier spacings of 15 kHz, 30 kHz, (Frequency Range 1 (FR-1)), and 120 kHz (FR-2), cell bandwidths of 10, 20, 40, 60, 80, and 100 MHz, as well as 200 MHz (FR-2 only). The PHY also supports 4-layer Downlink (DL) and 2-layer Uplink (UL) Multiple Input, Multiple Output (MIMO) as well as highly efficient 3GPP compliant channel encoder and decoder (turbo, LDPC, polar).

The PHY can run entirely and in real-time on x86 architecture by leveraging its Single Instruction Multiple Data (SIMD) vector processing extensions. Layers 2 and above also run on ARM architectures. The DU can also make use of different kinds of hardware accelerators, both in-line and look-aside. The in-line accelerator makes use of the FAPI interface between the PHY and the MAC layer. Currently, OAI supports the NVIDIA Aerial Software Development Kit (SDK) Layer 1 [29, 30], but others will follow. The look-aside accelerator makes use of the Intel bb-dev interface and currently supports AMD Xilinx T1 and T2 cards [31, 32].

OAI implements both monolithic CU or disaggregated CUs (CU-UP and CU-CP). The CU-UP contains mainly the Service Data Adaptation Protocol

(SDAP) and Packet Data Convergence Protocol (PDCP) layers. The CU-CP features the Radio Resource Control (RRC) layer, for radio resource management and UE lifecycle management. The communication between the two happens over the E1 interface. Both CU-UP and CU-CP can handle multiple DUs. In addition, F1 handover between multiple DUs is supported. The handover can either be triggered manually or based on neighbor cell measurements and events.

Both OAI DU and CU implement the O-RAN E2 interface to the near-Real-Time (near-RT) RIC. The E2 agent supports service models Key Performance Measurement (KPM) v2.03/v3.0 and RAN Control (RC) v1.03. The E2 interface has been demonstrated successfully with the OSC RIC [33, 34], as well as with OAI's own implementation of the near-RT RIC called flexRIC [35, 36]. OAI DU and CU also implement the O-RAN O1 interface to Operations and Management software such as Open Network Automation Platform (ONAP) [37, 38].

The OAI DU and CU are compatible with many different open-source core networks such as the Open5GS [39], free5GC [40], and of course the OAI 5G Core (see Section 2.4) as well as many commercial core network solutions.

For detailed information on the OAI RAN project, we refer the reader to the *readme* file on the OAI git repository [41].

2.1.1. Roadmap

The following features are part of the roadmap for the RAN project. This implies that early-stage implementation efforts are already underway and will be refined and finalized in the near future.

Non-Terrestrial Network (NTN). NTN refers to the use of space-based infrastructure, such as satellites or high-altitude platforms, to provide 5G wireless communication services. 3GPP standardized support for NTN in Rel. 17. The support for NTN in OAI was developed jointly by Fraunhofer IIS, Allbesmart, and University of Luxembourg. It supports both Geosynchronous Earth Orbit (GEO) and Low Earth Orbit (LEO) transparent satellites, i.e., the Base Station (BS)'s signal is sent from the ground, received and amplified by the satellite before it is sent back to the UE on the Earth's surface. A first demonstration of the developments has been done in a series of papers [42, 43, 44]. The features are currently being integrated into the main branch of OAI.

Frequency Range 2 (FR-2). FR-2 refers to deploying the stack with a carrier frequency in the spectrum from 24.25 GHz to 71 GHz, also referred to as millimeter wave (mmWave). When operating in this frequency range, the use of large antenna arrays and beamforming is absolutely necessary to achieve the required link budgets. 3GPP has specified several beamforming procedures for initial beam acquisition, beam tracking, and mobility, as well as beam recovery. Apart from implementing these procedures as well as the other adaptations for FR-2 in OAI, the most difficult part is getting and setting up the necessary hardware. A first demonstration of OAI in mmWave was done at Mobile World Congress (MWC) 2024 with an USRP X410 and a RF frontend from Interdigital. While this frontend is no longer commercially available, similar performance can be achieved with the mmWave RF frontend from TMYTEK [45]. At MWC 2025 we also demonstrated the integration of OAI with a FR-2 O-RU from LiteOn.

Network Slicing and Dynamic Quality of Service (QoS) Support. As described in Section 2.4, the OAI CN already supports Network Slicing and QoS. At the level of the RAN, these features mostly affect the scheduler. While QoS ensures optimal performance for various types of data traffic or services by means of prioritization, network slicing tries to create orthogonal resources for different types of data traffic or services, and each slice employs its own scheduler. Orthogonality can be achieved, for example, through allocating different sets of resource blocks or bandwidth parts to different slices.

OAI already supports the configuration of multiple slices using the Single Network Slice Selection Assistance Information (S-NSSAI) and UEs can select the desired slice in the Packet Data Unit (PDU) session establishment. A preliminary version of the scheduler that allows for a static assignment of Physical Resource Blocks (PRBs) to slices has been shown in [46] and is currently being integrated into OAI. A scheduler that supports QoS has been developed in [47] and is also being integrated into OAI soon.

Geolocalization. 5G NR supports a wide range of positioning techniques, both network-based and user-based. One of the most common techniques is UL-Time Difference of Arrival (TDoA), which is based on synchronized measurements of the Time of Arrival (ToA) at different Transmitter Receiver Pairs (TRPs) based on the SRS UL signal. These UL ToA measurements are then sent via the New Radio Positioning Protocol a (NRPPa) protocol to the LMF, which performs the estimation of the UE position (see Section 2.4). A first demonstration of this can be found here [48].

The gNB also supports the transmission of Positioning Reference Signal (PRS) signals on the DL for UE-based positioning (see Section 2.3).

Sidelink. 5G NR Sidelink refers to a direct communication interface in the 5G New Radio (NR) standard that enables devices to communicate with each other directly through a set of new physical channels. Two independent implementations of these features in OAI were developed in [49] and [50], and OAI is currently working on merging these features and integrating them.

Massive MIMO. Today, OpenAirInterface supports MIMO with up to 4 layers in DL and 2 layers in UL. As mentioned above, OAI is also working on the integration of beamforming procedures. However, OAI does not yet support multi-user MIMO, i.e., spatially separating multiple users on the same time-frequency resources by means of beamforming or precoding. This is usually achieved by means of massive MIMO O-RUs with 32 or more TX and RX chains. These RUs can be operated either on a set of pre-defined beams or by providing weights for the beams that the DU determines based on UL channel measurement (channel reciprocity). While the first one is easier to implement, the latter provides better performance. OAI will develop work to support Massive MIMO in the OAI O-DU solution, including computation of beam weights based on channel reciprocity, MAC scheduling, as well as support for in-line acceleration through the FAPI interface.

2.2. FlexRIC

FlexRIC [35] is an open-source implementation of a near-RT RIC, E2 Agent, and xApp SDK. It supports E2 Application Protocol (E2AP) v1.0/2.0/3.0 and O-RAN Service Models (SMs) i.e., KPM v2.01/v2.03/v3.0 and RC v1.3, as well as *à la carte* defined SMs i.e., MAC, RLC, PDCP and GTP. Additionally, xApps can be developed using C/C++ and Python3, easing developer experience, and the provided SDK already integrates an SQLite database to facilitate further data analysis. FlexRIC can run on ARM and x86 architectures, as most of its code is strict C11. Moreover, its one-way delay latencies from the RAN to the xApp are below 1 ms, which makes it suitable for real-time scenarios, e.g., traffic flow manipulation. In fact, the importance of traffic control within the RAN has already been demonstrated using *à la carte* TC SM [51] on top of OAI, showing FlexRIC project capabilities to handle messages below one millisecond, demonstrating its suitability for real-time scenarios. Contrary to other projects that sacrifice standard compatibility aiming to achieve low-latency [52, 53], FlexRIC is 100% O-RAN compliant, and its interoperability has been shown with OAI RAN, OSC RIC, Keysight RICTest [54, 33], as well as srsRAN [55]. Lastly, due to FlexRIC's O-RAN standard implementation completeness and thanks to OAI's permissive liberal Public License, its SMs have been ported to other near-RT RIC platforms [56] and integrated into other testing platforms [57].

2.3. User Equipment

For a long time, the OAI UE implementation was primarily a tool for testing the OAI RAN and core network, so its functionality has been limited to the features specifically required by the RAN. Moreover, little effort was made to ensure the OAI UE was as stable as the RAN. However, this has changed in recent years, and the UE has undergone significant improvements. Indeed, the software-defined UE plays a key role in testing algorithms and protocol stack improvements that span both the RAN and the UE side. Further, it allows for the deployment of software-defined end-to-end cellular networks in a variety of testbeds and experimental environments, including Colosseum, the world's largest wireless network emulator with SDRs in the loop. A complete list of features supported by OAI UE can be found here [58].

One of the main recent achievements has been to make the OAI UE compatible with third-party gNBs [59]. In this demonstration, we used a Nokia gNB and an OAI soft-UE with a USRP B210 as a radio frontend. One of the main challenges was managing the latency in the OAI UE inherent to the USRP. The latency between DL and UL processing restricts how quickly the OAI UE can send an Acknowledgement (ACK)/Negative Acknowledgement (NACK) after a Physical Downlink Shared Channel (PDSCH) reception (parameter k_1 [60]), or how fast the UE can transmit on the Physical Uplink Shared Channel (PUSCH) after receiving a UL Downlink Control Information (DCI) on the Physical Downlink Control Channel (PDCCH) (parameter k_2 [61]). Most commercial gNBs are configured with short default values for these parameters, typically just 2 slots. However, setting these values to 4 slots allowed the UE to successfully attach to the gNB and initiate a PDU session.

2.3.1. Roadmap

The roadmap for the OAI UE has two main objectives. First, we aim to improve both latency and throughput. Second, we are introducing new capabilities to bring the UE's feature set on par with that of the gNB.

Reducing Latency. To be able to support k_1 and k_2 values (see Section 2.3) of less than 4 slots, the latency in the UE has to be reduced. While the latency introduced by the USRP is fixed, we can make the processing more efficient by restructuring the PHY layer to shorten the processing time of physical signals. The main idea is to process received signals on a symbol basis rather than on a slot basis at the PHY layer. This restructuring would allow the PHY layer to process DCI much faster, without waiting for the full slot duration. The same principle can be applied to other PHY signals. Combined with the recent optimization in PUSCH signal generation, experiments have shown that after restructuring, the minimum k_1 and k_2 values for normal UE operation were reduced by 1 slot, bringing them to 2 slots for 30 kHz Sub-Carrier Spacing (SCS).

NTN. As mentioned in Section 2.1, 3GPP Rel 17 NTN are currently being integrated into the OAI RAN. Due to the lack of commercial UEs supporting NTN, an implementation of the corresponding features in the OAI UE is also available. This functionality was demonstrated successfully with a real GEO satellite [44, 43], as well as with a LEO one [62].

Geolocalization. 3GPP Release 16 introduced the PRS, which allows users to determine their location autonomously by using a DL-TDoA method. The HOP-5G project [63, 64] sponsored the development of the PRS in OAI for DL-TDoA positioning for FR1 and FR2, demonstrating the feasibility of these techniques. Based on this work, [65] built a testbed with three OAI gNBs and one OAI UE leveraging the PRS transmissions for DL-TDoA positioning. More recently, a novel framework presented in [66] estimated the Round Trip Time (RTT) between UE and gNB with existing 5G NR signals.

RAN Slicing. Another use case for the OAI UE is RAN slicing, where the UE can handle multiple PDU sessions across different slices. Users can interact with the UE through the AT command interface to define PDU contexts with specific S-NSSAI values, and request the network to establish PDU sessions, similar to commercial serial port-based 5G modems. This functionality is particularly useful for testing RAN slicing in controlled environments like the *Colosseum* testbed. Moreover, many 5G COTS UEs do not yet support multiple slices.

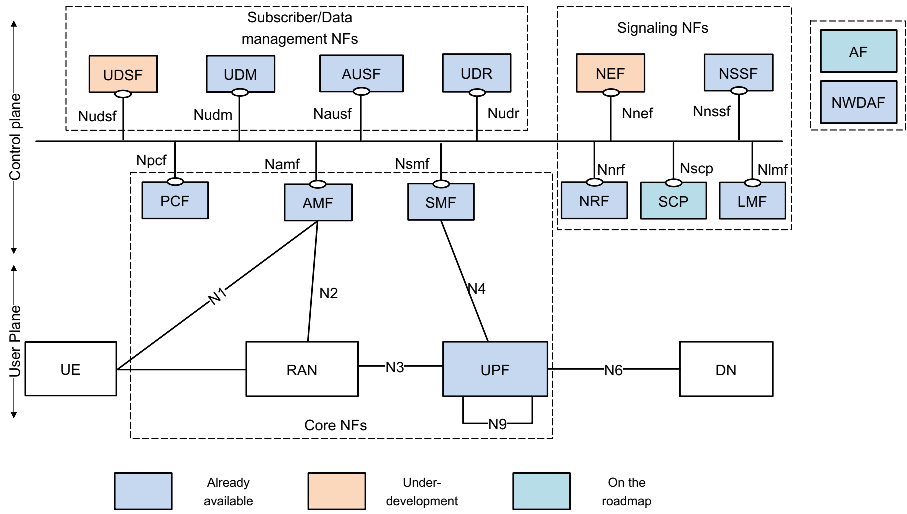

Figure 3: OAI 5GC Compoments

Figure 3 depicts the 5G system architecture with its main Network Functions (NFs). The 5G system architecture relies on the SBA to make the functional architecture more suitable for cloud deployment and to provide a flexible framework to meet the needs of a variety of applications and service types in 5G. In the SBA, the system functionality is achieved by a set of NFs providing services to other authorized NFs to access their services through a Service Based Interface (SBI). In other words, the NFs communicate with each other via SBI using cloud-friendly protocols such as HTTP/2 for transport and JavaScript Object Notation (JSON) as the serialization protocol. The centerpiece of the SBA is the Network Repository Function (NRF), which provides basic NF services including authorization, registration/deregistration, and discovery.

The OAI 5G Core (5GC) complies with 3GPP specifications and offers valuable propositions beyond the standards. Figure 3 shows the current status of OAI 5GC components from the latest release, rel 2.1.0. In this release, OAI 5GC supports 11 NFs, including Access and Mobility Management Function (AMF), Session Management Function (SMF), UPF, Authentication Server Function (AUSF), Unified Data Management (UDM), Unified Data Repository (UDR), NRF, Network Slice Selection Function (NSSF), Policy Control Function (PCF), Network Data Analytics Function (NWDAF), and LMF. Two NFs are currently under development, including Network Exposure Function (NEF) and Unstructured Data Storage Function (UDSF), and additional NFs, including Service Communication Proxy (SCP) and Application Function (AF), will be integrated into the OAI 5GC ecosystem in the upcoming releases.

OAI 5GC supports fundamental 3GPP procedures, including connection, registration, and mobility management procedures (e.g., registration management and service request procedures), as well as session management and N4-related procedures. These capabilities enable the OAI 5GC to support multiple UEs attaching to the network and establishing multiple PDU sessions concurrently. Additionally, OAI 5GC provides basic functionality to support the SBA, including NF registration and discovery.

The OAI 5GC also supports several advanced 3GPP procedures and features, including: (i) N2 handover procedures; (ii) event exposure services, which enable third-party applications to collect UE statistics and dynamically configure the OAI 5GC based on the collected information via customized APIs; (iii) network slicing-related procedures (OAI 5GC supports network slicing per UE and per PDU session); (iv) support for multiple UPFs within the same data path, along with the UL Classifier feature. These capabilities enable selective traffic routing to a Data Network (DN) located near the Access Network (AN) serving the UE and support service and session continuity mode 3.

Flexibility is a key driver of 5G adoption. OAI 5GC provides different flavors of 5GC for both the control and user planes, targeting different 5G applications and use cases. For the user plane, OAI 5GC provides different UPF implementations. Among them, we highlight: (i) the simple-switch UPF, which is easy to deploy and manage, offering sufficient performance for most use cases and therefore well-suited for tasks such as functional testing and validation; (ii) the Extended Berkeley Packet Filter (eBPF)/eXpress Data Path (XDP)-based UPF, a soft-UPF designed to provide a high-performance data path to meet the requirements of various 5G and beyond scenarios. Deployment flexibility is also a key consideration. OAI 5GC can be deployed in a variety of environments, ranging from traditional servers or Virtual Machines (VMs) to cloud-native platforms using tools such as Docker Compose or Helm charts.

More advanced features include:

- Network data analytics and data collection. The NWDAF collects data from various NFs and performs analytics to provide insights into the performance and health of the network. Combined with event exposure services, NWDAF can serve as a solid foundation for AI/ML-based decisions to enable automated deployment, management, and optimization of mobile networks.

- Support for location services. The LMF relies on measurements and assistance information from the RAN (via the NRPPa protocol) and the UE (via the LTE Positioning Protocol (LPP) protocol) to compute the position of the UE. The first version of the LMF includes algorithms to support UL-TDoA localization based on ToA measurements from multiple gNBs. The AMF has also been updated to support location services management and to facilitate the transport of location-related messages exchanged between the RAN/UE and the LMF.

- Quality of Service. QoS refers to the ability to provide differentiated packet forwarding treatment for user data traffic, ensuring specific performance levels such as packet error rate, throughput, delay, and latency.

> In 5G, the QoS model is based on QoS Flows, which represent the finest granularity of QoS differentiation within a PDU session. To support this architecture, OAI 5GC implements a set of Control Plane features across the SMF, PCF, and UDM. On the User Plane side, OAI UPF, leveraging eBPF, plays a pivotal role in enforcing QoS and policy rules, offering a promising solution for QoS support in 5G.

2.4.1. Roadmap

For the upcoming releases, the OAI 5G CN will continue to advance its cloud-native and automated deployment model by supporting stateless implementations and introducing additional customized APIs. The SCP will also be integrated into the OAI 5GC ecosystem to enable various modes of inter-NF communication, thereby supporting diverse deployment and operational scenarios. Finally, to lay the groundwork for Beyond-5G and 6G networks, OAI 5G CN will focus on key 5GC features, including QoS, network slicing, support for time-sensitive networking, and enhancements in security and reliability across the entire OAI 5GC ecosystem.

2.5. Management and Orchestration

While OAI provides essential 5G network functionalities, building a 5G network at scale also requires tools for managing cloud-native environments, as well as orchestration and automation of virtual network functions.

Open Source MANO (OSM) [67], a network service orchestrator proposed by ETSI, is a reference design based on ETSI Network Function Virtualization (NFV) standard and proposes multiple packages to deploy OAI 5G CN and RAN functions.

ONAP [68] is an end-to-end network service orchestrator that provides capabilities to manage physical, virtual machine-based, and cloud-native network functions. Certain components of ONAP are also used to implement the O-RAN–proposed SMO. While ONAP focuses on orchestrating and managing network services, Sylva [69] focuses on orchestrating telco-optimized Kubernetes clusters following cloud-native principles. When building a Kubernetes cluster, the specific requirements of 5G network functions, such as the UPF or RAN, are taken into account, including support for technologies like Single Root I/O Virtualization (SR-IOV), real-time kernels, and others. The Nephio project [70] enables not only the orchestration of Kubernetes clusters but also the orchestration of cloud-native network functions. It leverages GitOps principles along with Kubernetes declarative and reconciliation-based approaches to manage both Kubernetes clusters and cloud-native network functions. Together, all three projects enable the orchestration of end-to-end network services and the management of the underlying cloud infrastructure hosting the network functions.

3. Development Philosophy and Methodology

3.1. Importance of Open-Source Communities and their Collaboration

OSA, as the foremost open-source community in cellular wireless, understands its leadership role in promoting collaboration. Open source developments in the core technologies (RAN, CN, OAM software) of the cellular wireless industry suffer from a variety of challenges namely: (i) the need to maintain an expensive lab for testing and integration of software; (ii) the dearth of highly qualified engineers educated to MSc or PhD level; (iii) cut-throat competition between industry players making direct collaboration unsuitable. Despite these challenges, the value created by open-source reference implementations of a cellular wireless stack is recognized by all stakeholders in the academic community as well as industry for uses such as research and experimentation tools for future studies of the forthcoming standards. Under the circumstances, OSA has played a front-runner's role in bringing communities like ETSI, Linux Foundation Networking (LFN), OSC, and others together. The OSA leadership and engineers continuously engage with these bodies in thought leadership forums as well as in showcasing Proof of Concept (PoC) involving software assets from several communities. As 6G experimentation advances, OSA will play a pivotal role in enabling the sandboxes and experimental testbeds on the path to next-generation standardization.

3.2. Development Process

The development process at the OAI project is designed to facilitate high-quality software production, testing, and deployment for 4G and 5G networks. The OAI project is supported by a large international community, contributing to the development and testing of the software. The project emphasizes open collaboration, with resources and code available on GitLab [41].

Each of the project groups described in Section 2 follows a defined roadmap, with specific objectives and milestones that are published on the OAI website [27]. Moreover, each group holds regular open meetings for all the developers to synchronize their developments. This structured approach helps in tracking progress and maintaining alignment with overall project goals.

3.3. Contribution Guidelines

Before a developer can start contributing, they have to sign the OAI Contributor License Agreement (CLA), which basically states that the contributor adheres to the terms of the OAI public license and that they grant a copyright license of the contribution to the Alliance and to recipients of software distributed by the Alliance. In case the author's work is protected by a patent, the author is prepared to grant a license of these patents on FRAND terms to commercial users of the software.

The developer then creates the contribution, following the basic coding rules and the workflow described in the contribution guidelines of the OAI git repository [41]. Once the developer has completed the contribution, they create a merge request on the OAI GitLab page [41]. This will trigger both human review and automated Continuous Integration (CI) tests to evaluate whether a code contribution is ready to be merged.

3.4. Continuous Integration, Testing, and Deployment

The OAI project leverages a Jenkins-based CI/CD framework, which runs a set of pipelines every time a user creates a merge request on Eurecom's Gitlab server. There are two sets of pipelines: one set for building images and another set for running tests. The image build pipelines compile the code and also perform static code analysis to catch issues early. The test pipelines run a number of tests, mostly on the various testbenches available at the Eurecom Open5Glab (see Section 4.1) but also on external testbenches such as Colosseum (see Section 4.3).

Most of the tests involve Over-the-Air (OTA) testing with either COTS UEs such as Quectel or with UE testers such as the Amarisoft UE tester. These tests are complemented with simulation tests, which can either be unitary tests of a specific feature or end-to-end tests using OAI RF simulator. We test 4G, 5G NSA, and 5G SA configurations using either the OAI 4G or 5G CN, as well as third-party CNs. The tests typically include attach and detach procedures, along with basic connectivity checks using tools such as ping and iPerf. More details can be found in [71].

As an example for an external testbench, Colosseum has been integrated with the OAI CI/CD pipelines to trigger automated tests on the channel emulator, and report results back to the CI/CD. Tests can set different test parameters, such as the OAI branch to test, as well as the RF scenario to emulate during the test. Parameters are passed to an Ansible instance within Colosseum that builds container images for the specified OAI gNB and UE, and benchmarks the performance of the softwarized protocol stacks, leveraging Colosseum automated batch jobs and USRP X310 SDRs as RF transceivers. Once tests are complete, results are processed by Colosseum and summarized into a test report page, which also compares the most recent test with the history of results built over time, and can determine the final outcome of the test (e.g., test passed or failed) based on some criterion set by the developers. Finally, test report, results, and logs are stored in the EURECOM CI/CD, while the test history is maintained on the OpenRAN Gym website [72].

About every week, all the merge requests that have been accepted are combined into an integration branch. The integration branch is tested again with the CI pipeline, and if successful, it is merged into *develop* branch and tagged with the year and week number (*year.week*). At the same time, the Docker images according to that tag are pushed to Docker Hub [73].

3.5. Performance

The performance achievable with OAI depends on a variety of factors. These include the configuration of 5G NR parameters, such as bandwidth and TDD settings, as well as the type of radio hardware used, whether SDRs or O-RUs.

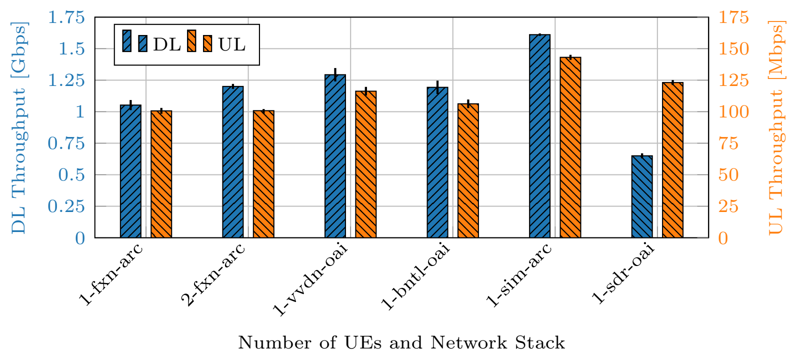

Figure 4: Performance profiling of peak DL and UL throughput using iPerf. The configurations on the x-axis use the following nomenclature: $number\_of\_UEs - RU\_type - L1\_type$.

The choice of UE, whether COTS devices or those based on SDR and OAI, also plays a significant role. Additionally, performance is influenced by channel conditions and the number of users connected to the system.

Figure 4 presents results from a selection of configurations, described on the x-axis using the following nomenclature: $number\_of\_UEs - RU\_type - L1\_type$. We include results for: 1 and 2 UEs; RU types including Foxconn (*fxn*), Benetel (*bntl*), VVDN (*vvdn*), RuSIM/CoreSIM (*sim*), and USRP SDR N310 (*sdr*); and Layer 1 implementations from NVIDIA (*arc*) and OAI (*oai*). For NVIDIA Aerial configuration, we use an NVIDIA Grace Hopper 200 server, while for the OAI Layer 1 configuration, we use an AMD EPYC9374F 32-core CPU. The results leverage a DDDSU TDD pattern (DDDDDDDSUU for *fxn*) and a 100 MHz bandwidth, 4 TRX antennas (2 for *sdr*), 4 layers in the DL (2 for *sdr*), 1 layer in the UL, and up to 256 QAM. The OTA measurements are done in an indoor laboratory environment with static UEs at fixed locations while the frequency band varies depending on the capabilities of the RU. In the simulated cases, measurements are done with a Keysight RuSIM device, which emulates the RU, the wireless channel, and the UEs, and Keysight CoreSIM to emulate the CN [74]. We use the *ExcellentRadioConditions* channel model, which simulates a full-rank MIMO channel with high Signal-to-Noise-Ratio (SNR). Regarding the special slot, due to hardware limitations, it is not utilized in the *fxn-arc* experiments, resulting in a lower DL throughput compared to the other cases, particularly in the 1 UE scenario (see [75] for a detailed explanation). In the *vvdn-oai*, *bntl-oai*, and *sdr-oai* configurations, we use 8 DL and 2 UL symbols, while in the *sim-arc* case, 12 DL and 1 UL symbols are used.

In the emulated *sim-arc* test cases, we achieve an average throughput of 1.61 Gbps in the DL and 143 Mbps in the UL with a single UE, which is very close to the theoretical peak throughput. In the OTA tests, the average throughput drops to 1.3 Gbps in the DL and 116 Mbps in the UL for the case *vvdn-oai* and to 1.2 Gbps in the DL and 100 Mbps in the UL for the case *fxn-arc*.

Additionally, the RuSIM equipment supports an arbitrary number of UEs

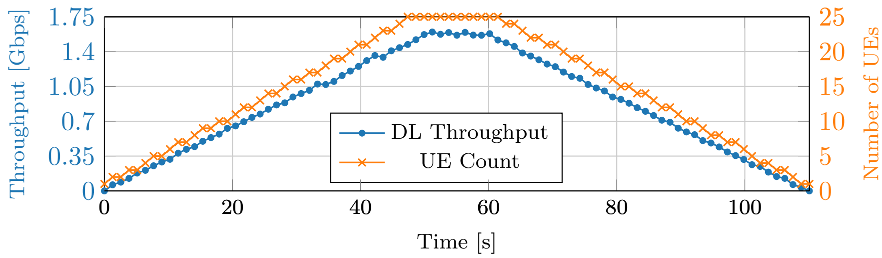

Figure 5: Performance profiling leveraging X5G with OAI NVIDIA Aerial and Keysight RuSIM/CoreSIM. The results show the downlink throughput as UEs progressively attach, each pushing approximately 64 Mbps, until reaching a total of 25 and a peak of 1.6 Gbps, and then gradually disconnect.

for stress-testing the system. Figure 5 shows the performance achieved as UEs progressively attach, each pushing approximately 64 Mbps, until reaching a total of 25 UEs and 1.6 Gbps, and then gradually disconnect. This demonstrates how OAI can sustain a high number of simultaneously attached devices with fair resource sharing and no noticeable performance degradation. Moreover, other stress tests with this configuration have allowed up to 55 UEs to remain attached at once, each running a *ping* test to verify connectivity, further demonstrating the reliability of the network stack.

When using an SDR instead of an O-RU, performance is typically lower. While it is theoretically possible on a USRP N310 SDR to drive four channels at 100 MHz each, in practice it is challenging to sustain the required fronthaul throughput without incurring real-time faults. However, two channels at 100 MHz each perform reliably, achieving 650 Mbps in the DL and 123 Mbps in the UL [76].

When using an SDR- and OAI-based UE, performance remains significantly lower than that of a COTS UE. The best throughput measured so far is 70 Mbps in the DL and 25 Mbps in the UL. This has been achieved on the Colosseum testbed (see Section 4.3), which also maintains a historical record of the pipeline's results, which we plot in Figure 6 [72].

Additional performance results of OAI in various configurations can be found in the latest status reports of the different CI/CD pipelines [76]. However, it should be noted that these pipelines are not designed to maximize throughput, as their primary purpose is to test code stability rather than peak performance.

4. End-to-end Systems Powered by OAI

In this section, we provide a few examples of end-to-end testbeds that use OAI as well as other open-source projects. This list is by far not exhaustive but aims to give a few lighthouse examples.

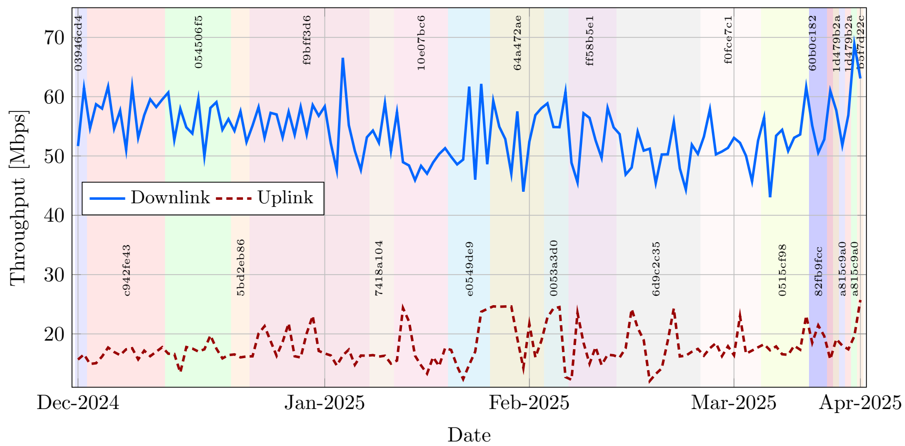

Figure 6: History of the DL and UL throughput measured in the Colosseum pipeline. The different colors and the numbers show the commit IDs of the develop branch.

4.1. EURECOM Open5GLab

The EURECOM Open5GLab is a cutting-edge research and experimentation facility focused on open and virtualized 5G networks based on the OAI open-source software. It consists of computing and radio infrastructure interconnected through high-speed fiber links and telecom-grade switches. The computing infrastructure includes Multi-core Intel Xeon, AMD EPYC, as well as Grace Hopper 200 servers, which are used for RAN, CN, and mobile-edge functions. Some servers also support inline acceleration (NVIDIA Aerial RAN CoLab Over-The-Air (ARC-OTA) [77]) as well as look-aside acceleration (AMD T2 card). Most of the computing resources are managed by Red Hat's OpenShift container platform, but some nodes can be used as bare metal by experimenters and developers. The radio infrastructure includes SDRs such as the USRP N310, X310, and B210, commercial split 8 RUs from AW2S, and commercial split 7.2 O-RAN RUs from Benetel, VVDN, and Foxconn. Some of these radios are deployed outdoors on EURECOM's roof where it has licenses to transmit in several 4G and 5G bands, such as Band 28 (700 MHz), Band n38 (2.6 GHz TDD), Band n78 (3.5 GHz TDD), Band n77 (3.8 GHz TDD), Band n258 (25 GHz TDD). Several COTS UEs, such as smartphones and modules, are also available in the lab. External access for onboarding software, collecting measurement data, and developing basic software for the site is available for partners using Secure Shell (SSH) access. Some of these resources are also used by OAI Jenkins-based CI/CD framework (see Section 3.4).

The EURECOM Open5GLab is part of the SLICES project, which is a large-scale European initiative focused on creating a flexible research infrastructure for digital and network technologies [78]. The deployment is documented in the SLICES 5G Blueprint, which allows other research sites to easily reproduce the setup [79].

EURECOM also hosts the drone4wireless lab [80], which focuses on autonomous flying robots for sensing and connectivity. It features multiple drones equipped with 4G and 5G radios used for various experiments [81, 82].

The outdoor deployment has recently been extended with the Firecell GEO-5G testbed, which consists of 3 RUs with distributed antennas and which is used for 5G-based geolocalization [48].

4.2. X5G

X5G is a multi-vendor, O-RAN-compliant private 5G network deployed in the Boston, MA, campus of Northeastern University [75]. It features the first-of-its-kind, 8-node deployment of the NVIDIA ARC-OTA framework [77], enabling the development and testing of next-generation wireless cellular networks on a programmable OTA platform with production-ready performance and capabilities.

As explained in Section 2.1, the upper layers of the protocol stack, namely the CU and DU-High, are deployed using the latest OAI software build, while the DU-Low utilizes the NVIDIA Aerial SDK. RUs from different vendors, including Foxconn RUs operating in the n78 band and a Keysight RU emulator, are integrated into the testbed. X5G incorporates CNs from various projects, such as OAI and Open5GS [39]. Finally, it includes the “E” release of the OSC near-RT RIC, integrated through a custom E2 agent in OAI [83], for the development of xApps.

All X5G software is containerized and deployed on a Red Hat OpenShift container platform cluster, enabling automation and orchestration of each component. The cluster comprises general-purpose hardware, including Dell, GIGABYTE, and Grace Hopper servers. Each GIGABYTE is equipped with an NVIDIA A100 GPU and Mellanox ConnectX-6 Dx Network Interface Cards (NICs), while each Grace Hopper features an NVIDIA Grace CPU Superchip, an NVIDIA H100 Tensor Core GPU, two BlueField-3 Data Processing Units (DPUs), and ConnectX-7 NICs. This configuration enables the execution of the NVIDIA Aerial GPU acceleration component.

X5G supports the use of COTS UEs, including devices from OnePlus, Apple, Samsung, and Pixel, as well as 5G modules such as Sierras and Quectel boards. Additionally, it supports the software UE developed by OAI and described in Section 2.3.

4.3. Colosseum

Colosseum is a publicly accessible testbed hosted at Northeastern University, part of the Platforms for Advanced Wireless Research (PAWR) project [84], as well as the world’s largest wireless network emulator with hardware-in-the-loop [85]. This SDR-based platform can be utilized as an Open RAN Digital Twin (DT) [86, 87], enabling researchers to test and develop end-to-end solutions for wireless networks.

Thanks to its Massive Channel Emulator (MCHEM), consisting of 128 USRPs X310 and a fabric of 64 FPGAs, Colosseum is capable of creating a DT

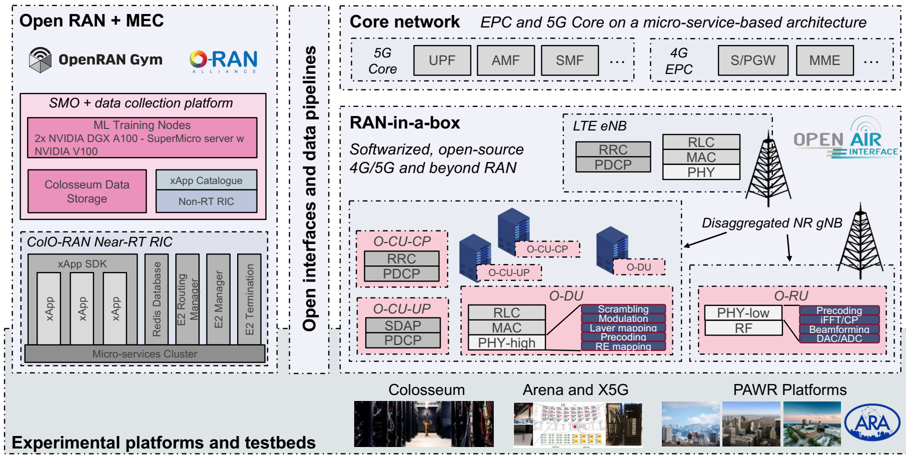

Figure 7: OAI and its role in the Open6G architecture deployed within Colosseum.

replica of a wide variety of real-world scenarios. Additionally, with its 128 Standard Radio Nodes (SRNs)—each comprising a general-purpose server and an additional USRP X310—users can remotely access the system via SSH, deploy wireless protocol stacks, and run various experiments in a repeatable, reproducible, and controlled environment. This capability is made possible by Colosseum's resource management framework, which facilitates the deployment of wireless solutions, such as OAI, from the CN to the software UE. Moreover, its CI/CD pipelines, described in Section 3.4, enable a Continuous Testing (CT) of the OAI software, for example, allowing the automatic testing of different releases across various DT scenarios. Similarly, CT pipelines in the OTA lab at Northeastern University enable the continuous testing of the OAI gNB with commercial smartphones and 5G modems [88].

Within Colosseum, OAI is part of the Open6G blueprint, a collection of software solutions that enable research on open and programmable networks. The Open6G blueprint, also shown in Figure 7, combines open-source elements, interoperable interfaces, and research platforms to enable end-to-end studies on various O-RAN and next-generation wireless solutions. The same can be deployed in Colosseum or on OTA platforms such as X5G, discussed above. OAI and this architecture have been featured in numerous Colosseum research projects and proof-of-concept solutions, both past and present. Tutorials on how to utilize OAI within the Colosseum platform are available on the OpenRAN Gym website [72], an open-source framework that promotes collaborative exploration and development in the O-RAN domain.

4.4. POWDER

The POWDER platform, located in the University of Utah campus in Salt Lake City, UT, supports 5G research by offering advanced hardware and software tools, enabling seamless transition from simulations to real-world tests in both indoor and outdoor environments. It provides access to multiple 5G profiles, OTA testing setups, and controlled RF environments, with various SDRs and 5G core networks like Open5GS and OAI. Researchers can create customized 5G networks, deploy RANs, and test novel applications such as spectrum sharing across networks. Outdoor experiments include mobile endpoints like campus shuttles equipped with 5G UEs [89].

4.5. ARA Lab

The ARA Wireless Living Lab at Iowa State University is a large-scale testbed advancing rural wireless technologies. It focuses on improving broadband and precision agriculture, supporting research in dynamic spectrum sharing, 5G/NextG, and low-latency communications. The ARA-O-RAN testbed is a subset of the ARA Wireless Living Lab running OAI on custom-made BS based on USRP N320 together with Tower-Mounted Boosters (TMBs) to amplify both transmitting and receiving signals and custom UEs built on USRP B210 with User Equipment Boosters (UEBs), akin to a smaller version of the TMBs. In their experiments, they were able to show a stable connection with UEs that are more than 1 km away [90, 91, 92].

4.6. AERPAW

AERPAW, or the Aerial Experimentation and Research Platform for Advanced Wireless, is a pioneering research platform hosted by North Carolina State University. It is focused on integrating Unmanned Aerial Vehicles (UAVs) into national airspace and advancing wireless technologies. The platform offers a software-defined, reproducible, and open-access environment for experimenting with 5G and beyond technologies. Similar to ARA, it features gNBs and UEs based on OAI and USRP SDRs with the key difference that the UEs can also be mounted on UAVs [93].

5. OAI Use-cases for 6G Research

While the official *develop* branch of OAI only accepts standard-compliant contributions, there is significant work utilizing OAI for 6G research. In this section, we would like to highlight a few of the advanced research works that are currently outside the scope of the standard and thus are not on the official OAI roadmap. A summary of these works is given in Table 1.

It is conceivable that one day this research work will become part of the standard, which means that the code can be merged into the *develop* branch. For example, this is what happened with the NTN project, where the initial functionalities were developed along with standardization, and the first demonstrations were done using an initial specifications draft. Later, when the specifications were finalized in 3GPP Rel 17, the initial code was adapted and merged into the *develop* branch of OAI.

Table 1: Summary of 6G challenges and use cases discussed in this section and list of related OAI-specific works.

6G challenge	OAI-related works
Exploring new spectrum	[94, 95, 96]
Air Interface Enhancements	[97, 98]
Architecture enhancements	[99, 100, 101]
Energy Efficiency	[102, 103, 104, 105]
Security and Resiliency	[42, 43, 44]

5.1. Exploring New Spectrum

Each new generation of mobile communication systems has introduced access to new spectrum bands, and 6G is no exception. The ITU has proposed a new frequency band, called the upper mid band or FR3, covering frequencies from 7.125 GHz to 24.25 GHz for 6G, expanding the currently defined FR1 (410 MHz $-$ 7.125 GHz) and FR2 ($24.25-71$ GHz) frequency ranges [106]. FR3 provides broader channels than FR1, while having lower propagation losses and cheaper hardware than FR2. It is more suitable for medium-coverage deployments and allows for efficient implementation of massive MIMO and 3D beamforming techniques [107].

Currently, SDRs or O-RUs for this frequency range are not widely available. One solution is to use external RF frontends together with a standard SDR such as the USRP. One such frontend has been developed by the company PiRadio and demonstrated in cooperation with Allbesmart [94]. The demonstration makes use of the OAI UE, since the FR3 parameters are not yet standardized.

Other challenges in the FR3 band are spectrum sharing since this frequency band is currently used by many other players. Although not done in FR3, OAI has been used to showcase such spectrum sharing capabilities [95].

Also, frequencies above the current limit of 71 GHz have been proposed for 6G. In the so-called sub-terahertz frequency range, loosely defined as 71 GHz to 300 GHz, very large chunks of frequencies are available. While technically it is possible to leverage this spectrum (there has even been a demonstration of OAI at 130 GHz [96]), many problems still need to be solved, especially the management of ultra-sharp beams and mobility.

5.2. Air Interface Enhancements

The 6G air interface will undergo significant advancements to enable ultra-high-speed, ultra-reliable, and intelligent communications. We expect the integration of AI/ML at different levels. Already in a 3GPP Rel. 18 study item, they explored the potential applications of AI and ML at the air interface level and their standardization [108]. The report identifies three key use cases: Channel State Information (CSI) feedback enhancement, beam management, and positioning accuracy enhancement.

CSI feedback enhancements are necessary to enable advanced multi-antenna processing such as cell-free MIMO, and massive MIMO. CSI is typically estimated by the UE and then fed back to the network in a compressed form. The accuracy of CSI directly influences the achievable spectral efficiency. Current CSI compression schemes are based on fixed rules and lack adaptability. However, deep learning-based CSI feedback has demonstrated superior performance compared to traditional methods [109]. One recent use case demonstration involving the OAI UE showcases an AI-enabled CSI feedback mechanism using an autoencoder on a real-time system [97]. This work demonstrates the capability of a programmable UE to integrate AI functions and validate them in real time.

Another hot technology for the 6G air interface is Reconfigurable Intelligent Surfaces (RIS). These are artificial surfaces embedded with programmable reflective elements, often made of meta-materials, that can control the behavior of electromagnetic waves. By dynamically adjusting these elements, RIS can improve signal propagation and network performance in wireless environments. The integration of RIS into a real network is still an open research question.

The 6G-BRICKS project addresses this challenge by integrating RIS into 5G RAN. This is achieved through the introduction of an RIS agent within the gNB and an RIS control xApp, which is responsible for configuring and managing the RIS. The project aims to showcase this innovative technology using the OAI platform, laying the groundwork for practical deployment and experimentation [98].

5.3. Architecture Enhancements

The O-RAN architecture with its open interfaces, RIC and xApps/rApps framework, as well as its data-driven approach, makes it the ideal environment for AI/ML integration. There are many examples where OAI is used to research and develop xApps and rApps using AI and ML techniques. In [99], the authors describe two xApps developed using OpenRAN Gym: a "sched" xApp that controls the scheduling policies for different classes of traffic, and a "sched-slicing" xApp that controls both the scheduling policies and the resource allocation (number of Resource Block Groups (RBGs)) for each network slice. Another example is [100] where the authors use reinforcement learning to optimize TDD patterns in the 5G system.

xApps typically operate on the order of tens of milliseconds and have only access to certain data that is shared over the E2 interface. However, some applications require even shorter latencies and also access to low-level data such as In-phase and Quadrature (IQ) samples. dApps were recently proposed as an extension of the O-RAN architecture. They are deployed directly on RAN nodes and can access data otherwise unavailable to RICs due to privacy or timing constraints, enabling the execution of control actions within shorter time intervals [101]. The authors also present a prototype based on OAI and performance results in two real-time control use cases: spectrum sharing and positioning.

5.4. Energy Efficiency

Energy efficiency has always been a design goal since the early days of mobile communication systems. In the context of modern 5G and future 6G networks, the focus increasingly shifts toward virtualized deployments. On one hand, virtualization can drastically reduce energy consumption in large-scale networks by pooling resources, dynamically reallocating them where needed, and placing unused cells into energy-saving modes. On the other hand, in smaller networks, virtualization may lead to higher overall energy consumption, as the infrastructure must be designed for peak load even when actual usage is low.

The use of hardware acceleration is one way of saving energy, and OAI supports both in-line and look-aside acceleration (see Section 2.1). Moreover, OAI can be used for experimentation with different energy-saving methods. For example, [102] uses OAI to experiment with management and orchestration frameworks that achieve energy efficiency improvements of 17.4% per UE and 78.3% per gNB. [103] presents a similar study but adopts different methods for estimating energy consumption in the network. [104], on the other hand, uses the Linux `perf` tool to profile CPU cycle counts and cache miss ratios, leveraging these metrics as proxies for energy consumption. Finally, [105] uses external power meters to measure the energy consumption of the radios only, specifically USRP SDRs, though the same approach can be applied to O-RUs.

5.5. Security and Resiliency

Just like energy efficiency, security has been a major design goal of mobile communication networks. While security leaks in 3GPP protocols have mostly been closed in 5G, current research focuses on security weaknesses in the new O-RAN interfaces. For example, [110] studies the impact of encryption on E2 interface as well as the Open Fronthaul interface using the X5G testbed (see Section 4.2). [111] on the other hand develops an xApp employing unsupervised anomaly detection and LLM-based expert referencing to detect and analyze emerging threats and anomalies at run-time. They demonstrate a prototype of their system on an O-RAN compliant cellular network testbed based on OAI.

5.6. Ubiquitous Connectivity

Ubiquitous connectivity in 6G refers to seamless, high-speed, and reliable network access available everywhere, anytime, for anyone and anything. One approach to achieving this is through the use of NTN, based on satellites or high-altitude platforms, to deliver 5G wireless communication services. Support for NTN with both GEO and LEO transparent satellites has been integrated into OAI and demonstrated in a series of papers [42, 43, 44]. In 6G, a tighter integration between terrestrial and non-terrestrial networks is expected.

6. Conclusions and Future Directions

This paper explored the OAI project, an open-source initiative that plays a pivotal role in the evolution of 5G and the future 6G networks. We presented the history and progression of OAI, its unique licensing model, and the various projects under its umbrella. We also highlighted the development methodology, CI/CD processes, and end-to-end systems powered by OAI. The open-source approach of OAI is emphasized as essential for tackling the challenges of 6G, fostering community collaboration, and driving innovation in next-generation wireless technologies. While AI and ML have come only as an afterthought within the already established 5G architecture and air interface, 6G will be the first standard to embrace AI natively [112].

Our vision for OAI is to establish it as the definitive reference implementation for 6G as the standard takes shape. Achieving this requires not only robust and reliable implementations of both the RAN and UE but also a forward-thinking architecture to support the integration of cutting-edge AI/ML algorithms. Seamless collaboration between RAN and UEs is critical to enabling researchers and developers to easily deploy and test their models. By leveraging frameworks such as O-RAN xApps on the RAN side and extending similar plug-and-play capabilities to the UE, OAI can foster innovation across all layers of the network. This will enable researchers to focus on groundbreaking advancements without being hindered by system integration challenges, paving the way for the development of 6G.

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